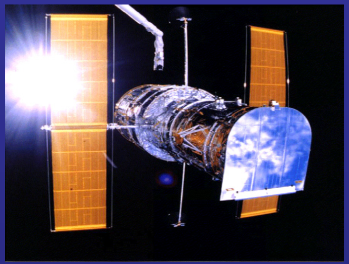
Beyond Spitzer

(Pasadena, June 2004)

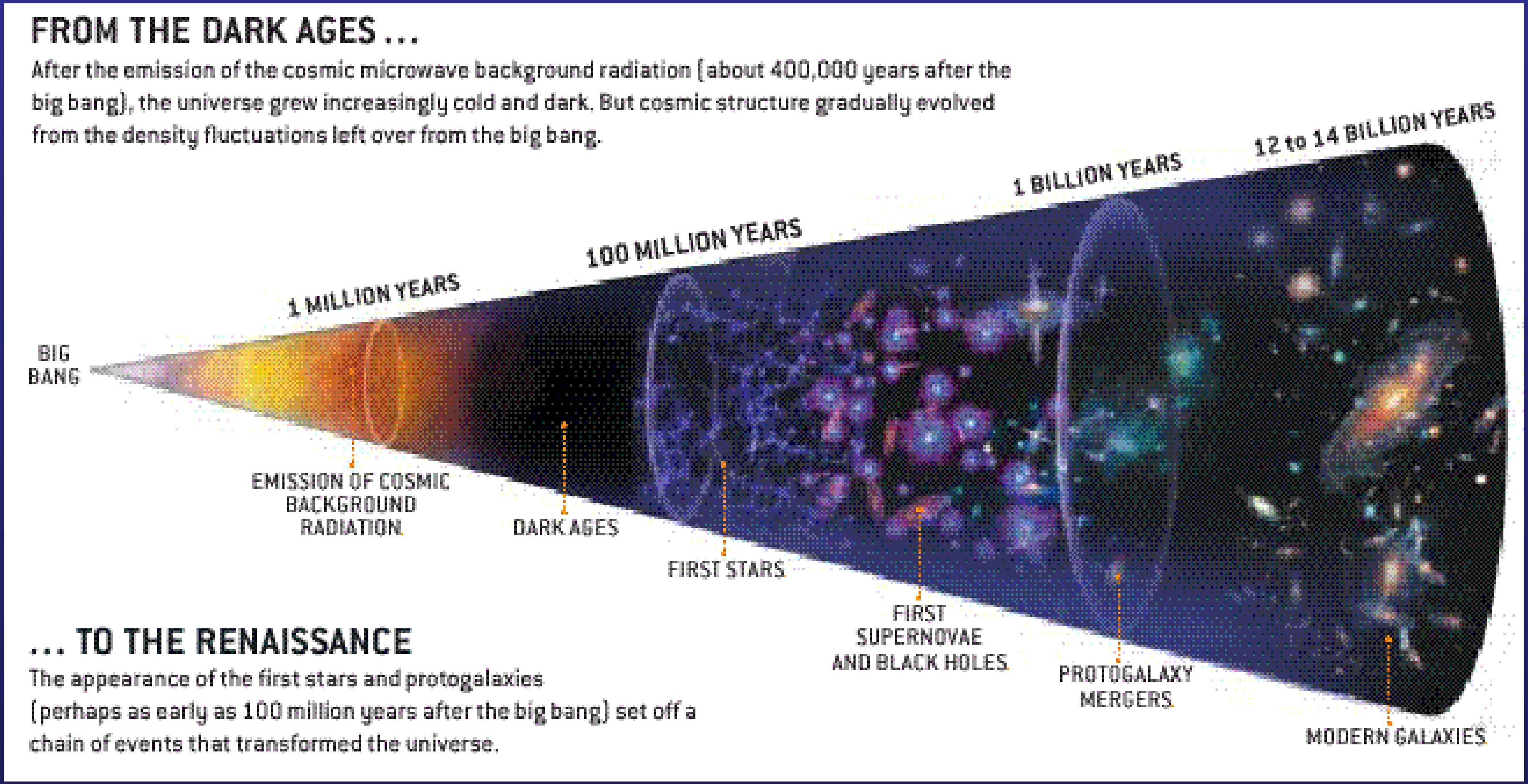


Infrared Radiation from the First Stars

Volker Bromm

Space Telescope Science Institute

From the Dark Ages to the Cosmic Renaissance

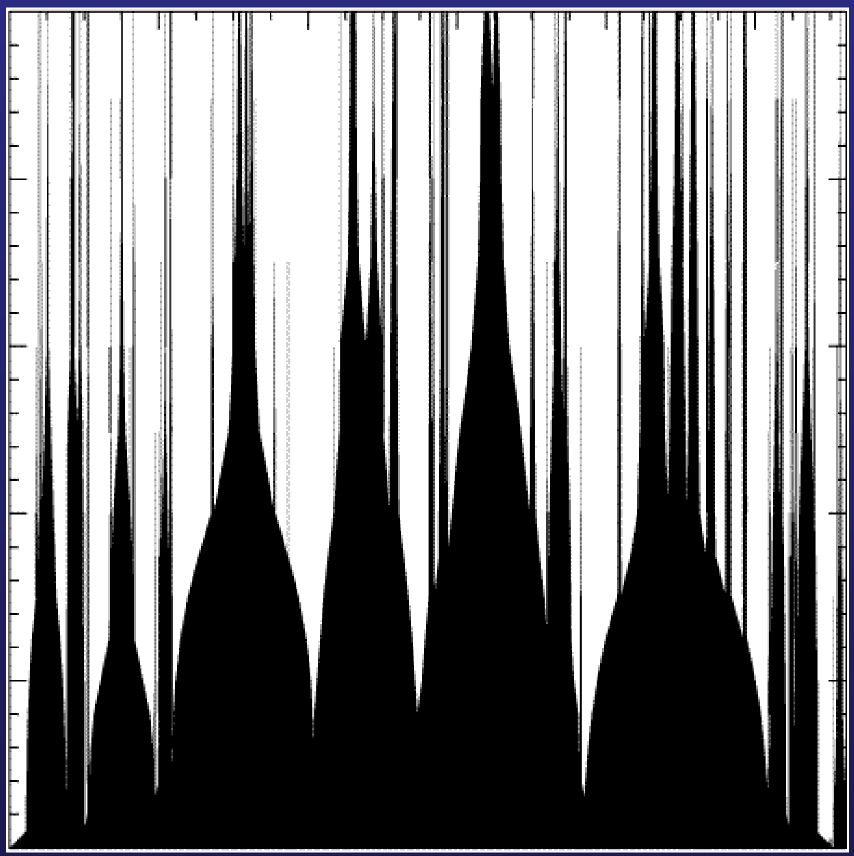


- First Stars → Transition from Simplicity to Complexity

Why Study Population III (=First Stars) ?

- The Quest for our Origins
- Importance for Cosmological Structure Formation
  - Reheat / Reionize the Universe
    - → Feedback effects on IGM
  - Initial enrichment with metals
    - → Pure H/He out of BBNS
    - → Need stars to synthesize heavy elements
  - Pop III remnants
    - → Baryonic DM (?)
- Upcoming Observations
  - CMB anisotropy probes (WMAP / Planck)
    - → Study imprint of first stars
  - IR missions (SIRTF/ JWST)
    - → Direct imaging

Hierarchical Structure Formation:

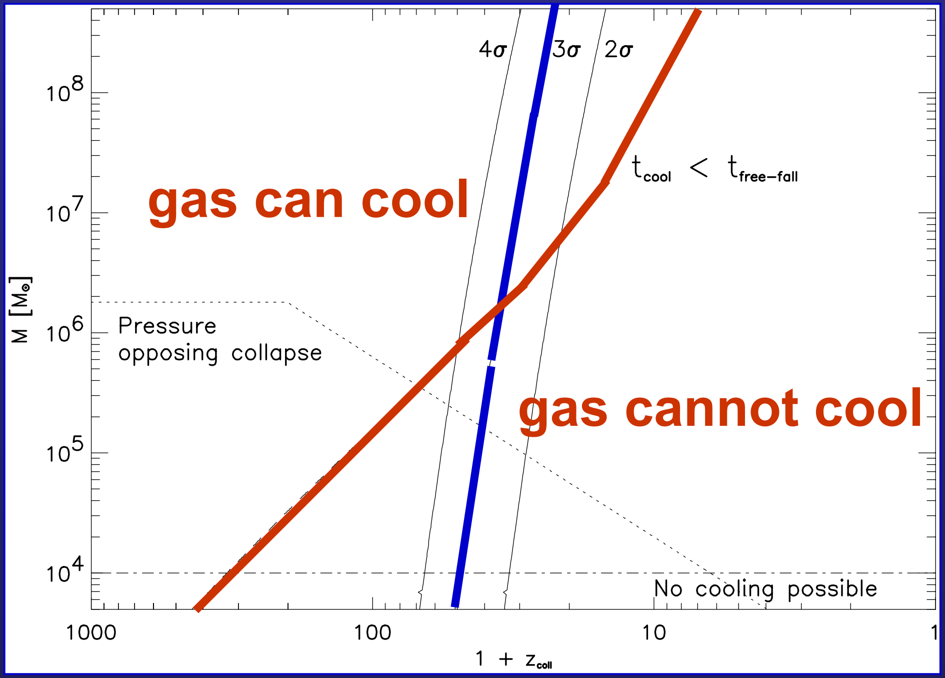


- Variant of CDM
- Typical mass scale of collapsed objects increases with time

(Beasley et al. 2002, MNRAS, 333, 383)

Region of Primordial Star Formation

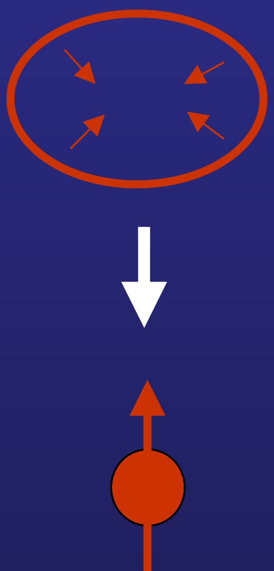
- Gravitational Evolution of DM
- Gas Microphysic:
  - Can gas sufficiently cool?
  - $t_{cool} < t_{ff}$ (Rees-Ostriker)

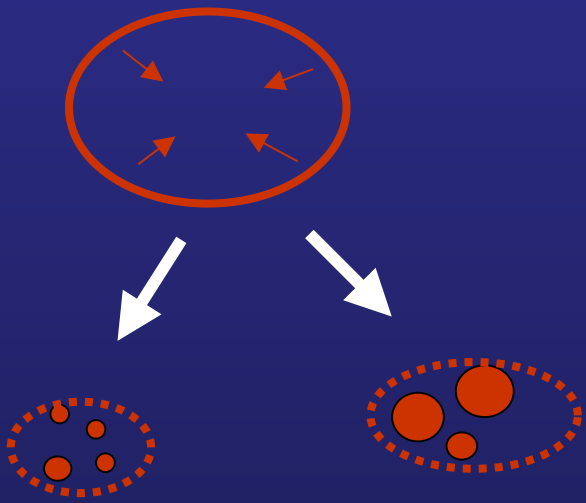


- Collapse of First Luminous Objects expected:
  - at: z_{coll} = 20 – 30
  - with total mass: $M \sim 10^6 M_o$

How massive were the First Stars?

$M \sim 10^6 M_o$





normal IMF

Top-heavy IMF

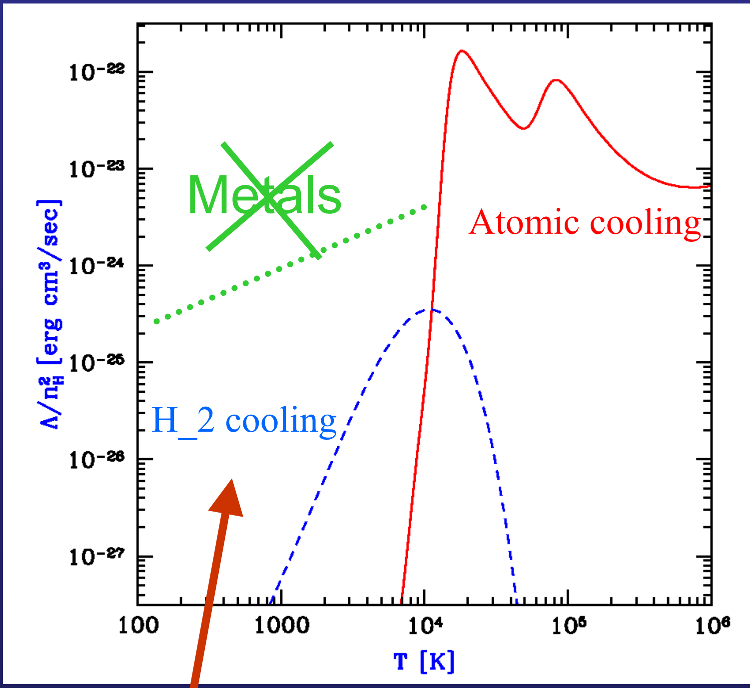
Massive Black Hole

Cluster of Stars

Previous estimates: $1\ M_o < M_{PopIII} < 10^6\ M_o$

The Physics of Population III

- Simplified physics
  - No magnetic fields yet (?)
  - No metals → no dust
  - Initial conditions given by CDM
    - → Well-posed problem
- Problem:
  How to cool primordial gas?
  - No metals → different cooling
  - Below 10^4 K, main coolant is H_2



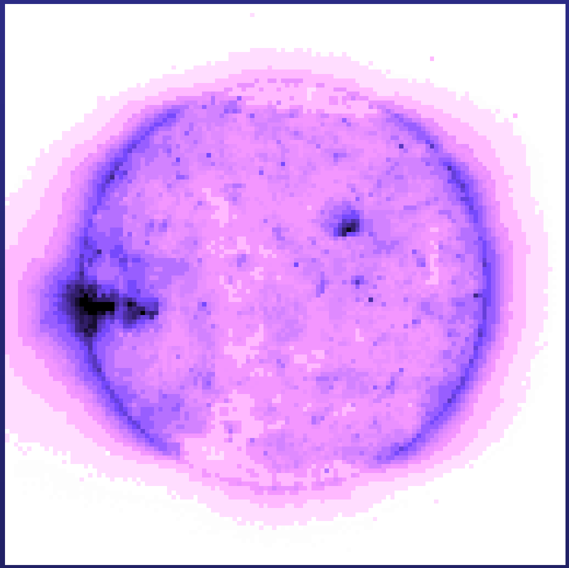
T_{vir} for Pop III

- H_2 chemistry
  - Cooling sensitive to H_2 abundance
  - H_2 formed in non-equilibrium
    - → Have to solve coupled set of rate equations

Simulating the Formation of the First Stars:

(Bromm, Coppi, & Larson and Bromm & Hernquist)

- Use TREESPH / Gadget (both DM and gas)
- Radiative cooling of primordial gas
- Non-equilibrium chemistry
- Initial conditions: ΛCDM
- Modifications to SPH:
  - sink particles
  - particle splitting

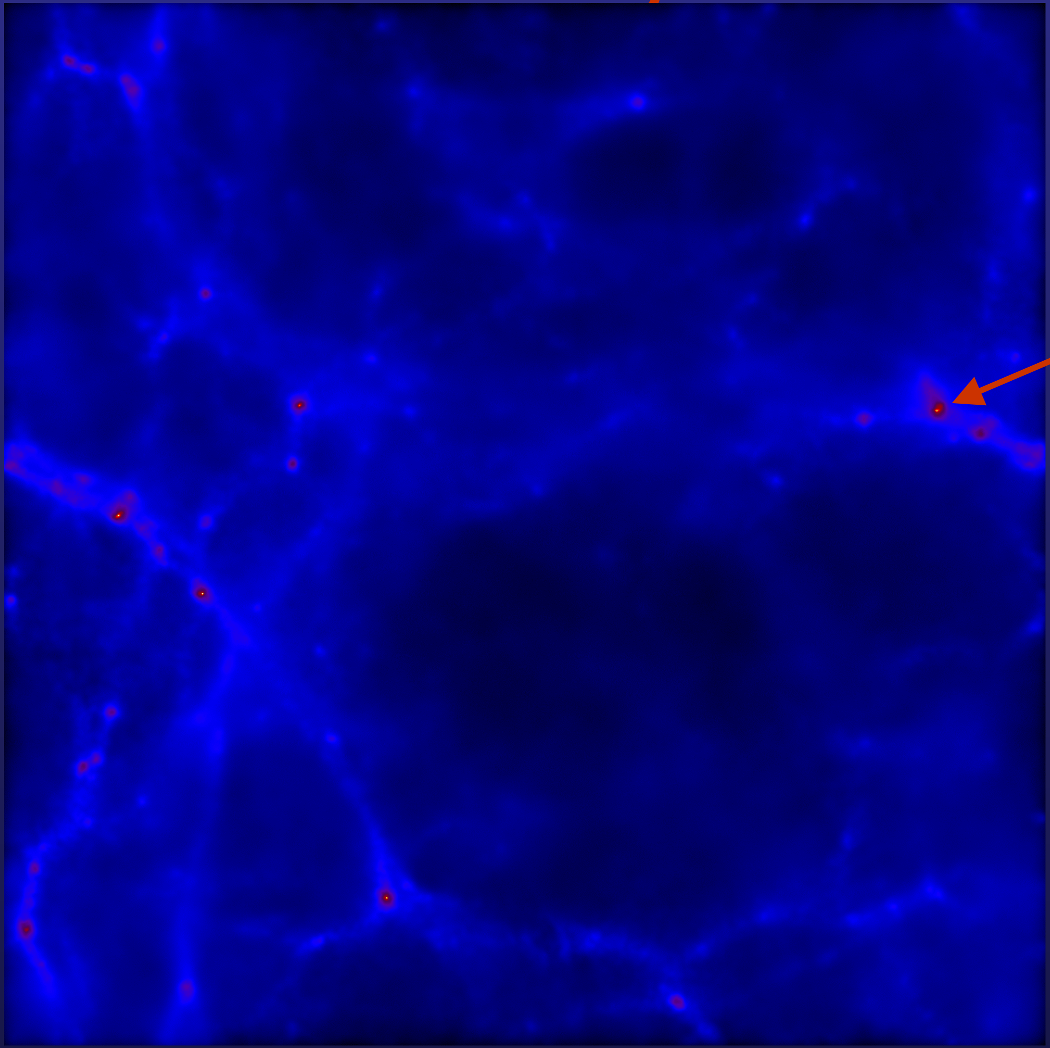


Cosmological Initial Conditions

- Consider situation at **z = 20**

Gas density

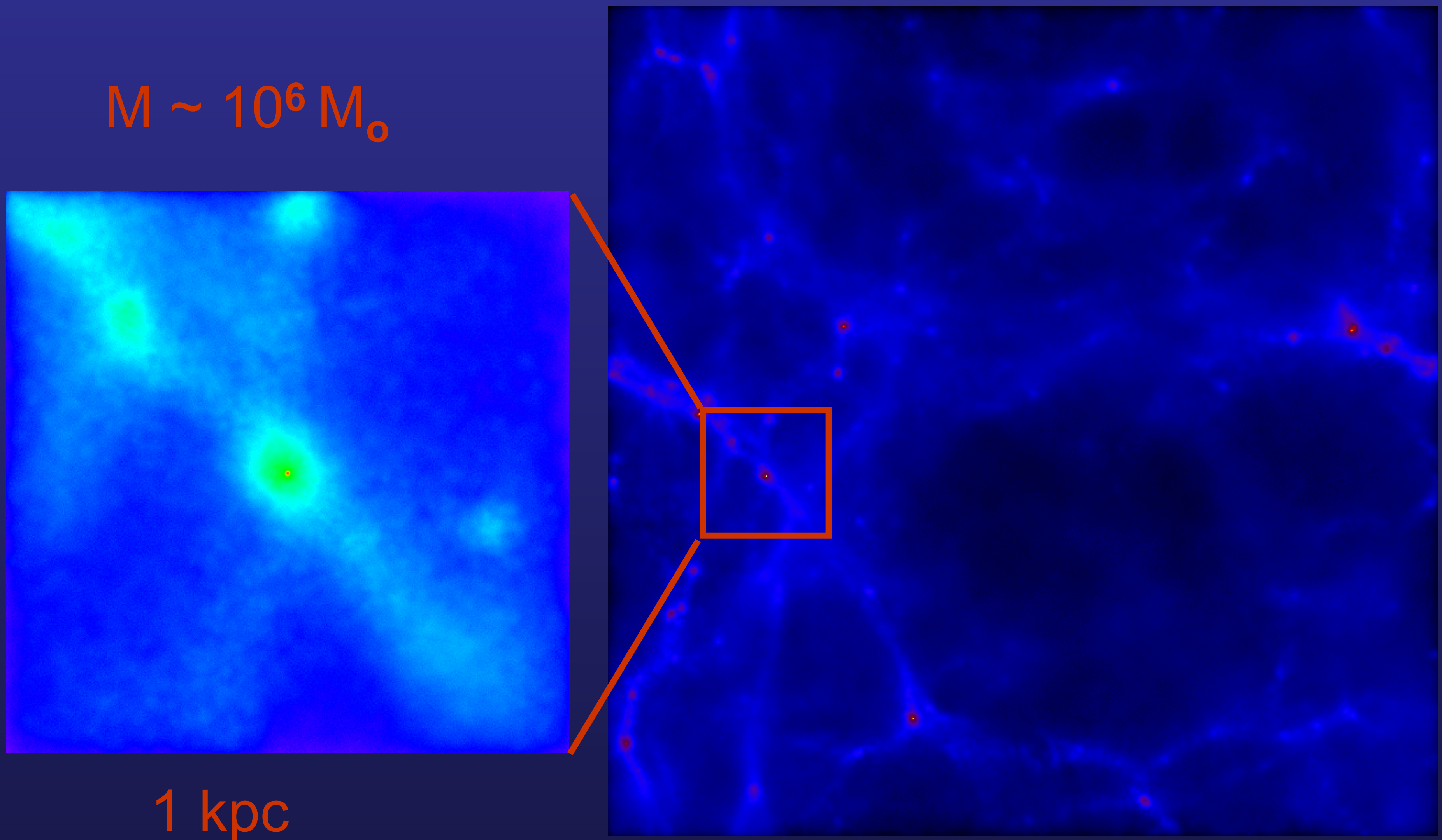
~ 7 kpc



Primordial Object

The First Star-Forming Region

$M \sim 10^6\ M_o$

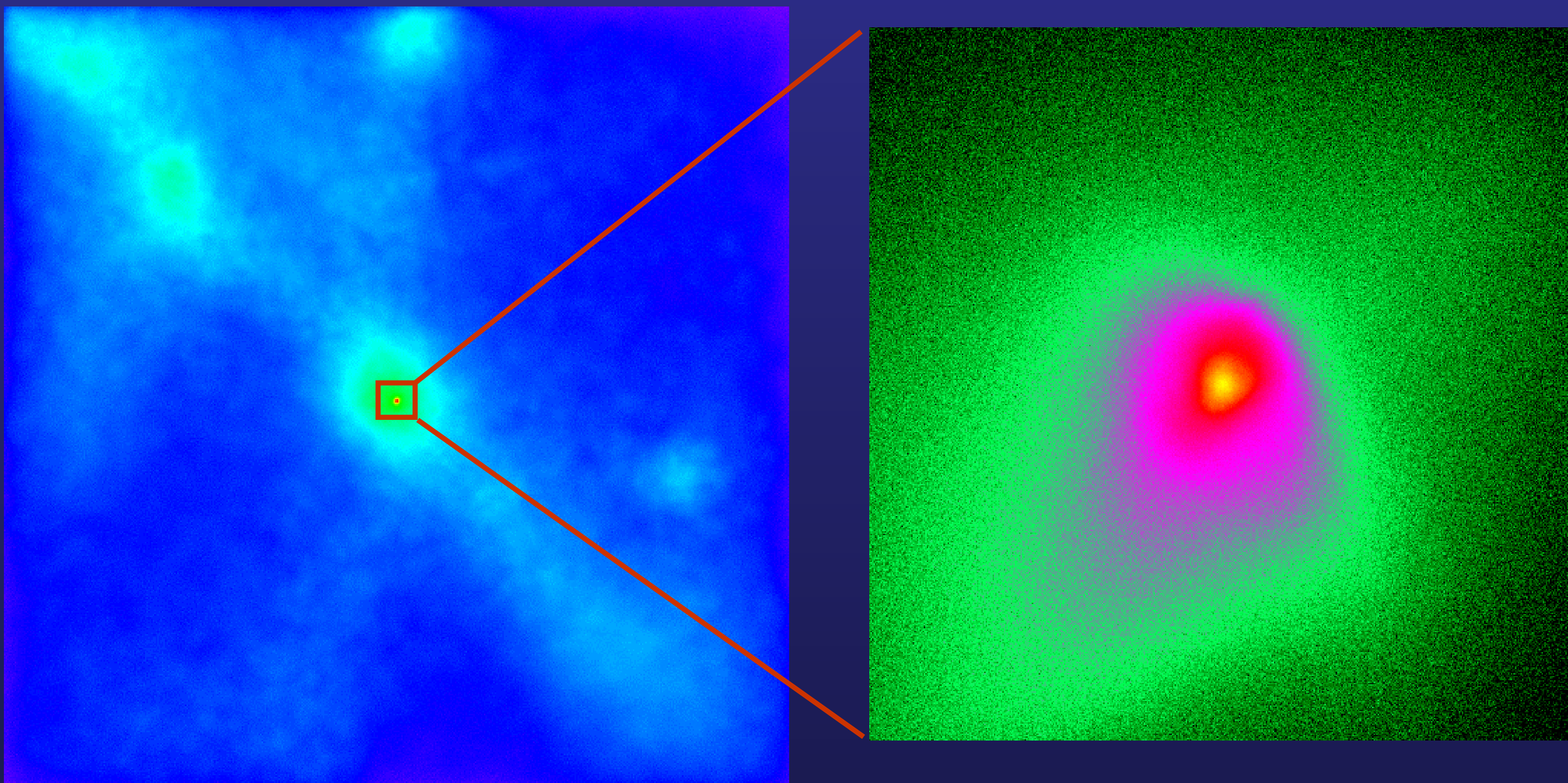


1 kpc

~ 7 kpc

Formation of a Population III Star

$M_{halo} \sim 10^6 M_o$ $M_{clump} \sim 10^3 M_o$



~ 25 pc

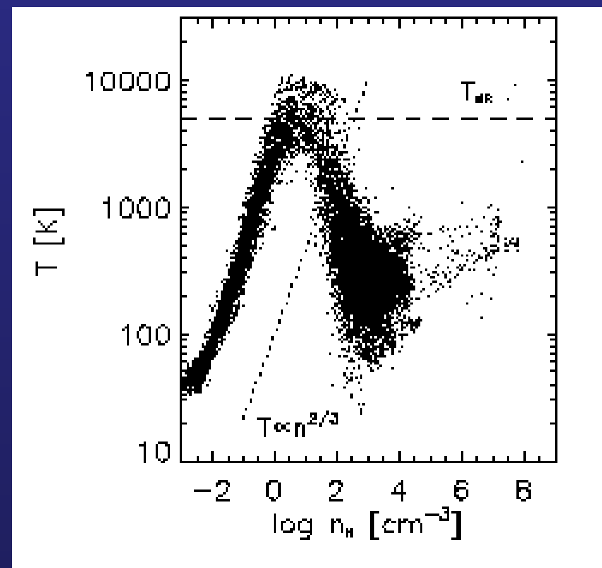
1 kpc **(see also Bromm, Coppi, & Larson 1999, 2002)**

A Physical Explanation:

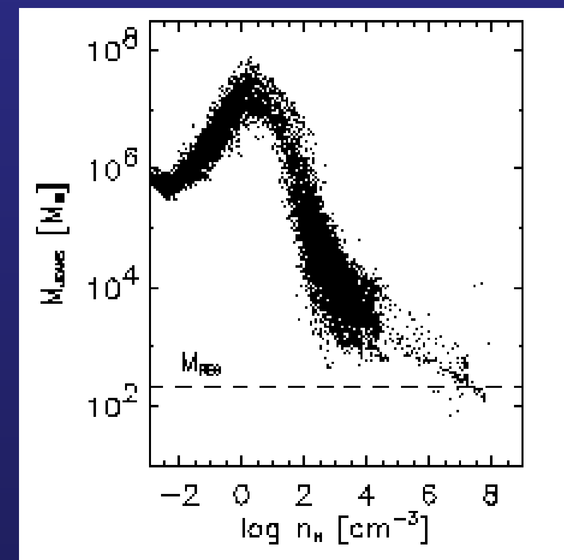
- Gravitational instability (Jeans 1902)
- Jeans mass: $M_J \sim T^{1.5}\, n^{-0.5}$

- Thermodynamics of primordial gas

T vs. n



M_J vs. n



- Two characteristic numbers in microphysics of H_2 cooling:
  - $T_{min} \sim 200$ K
  - $n_{crit} \sim 10^3$ - 10^4 cm^{-3} (NLTE $\rightarrow$ LTE)
- Corresponding Jeans mass: $M_J \sim 10^3\, M_o$

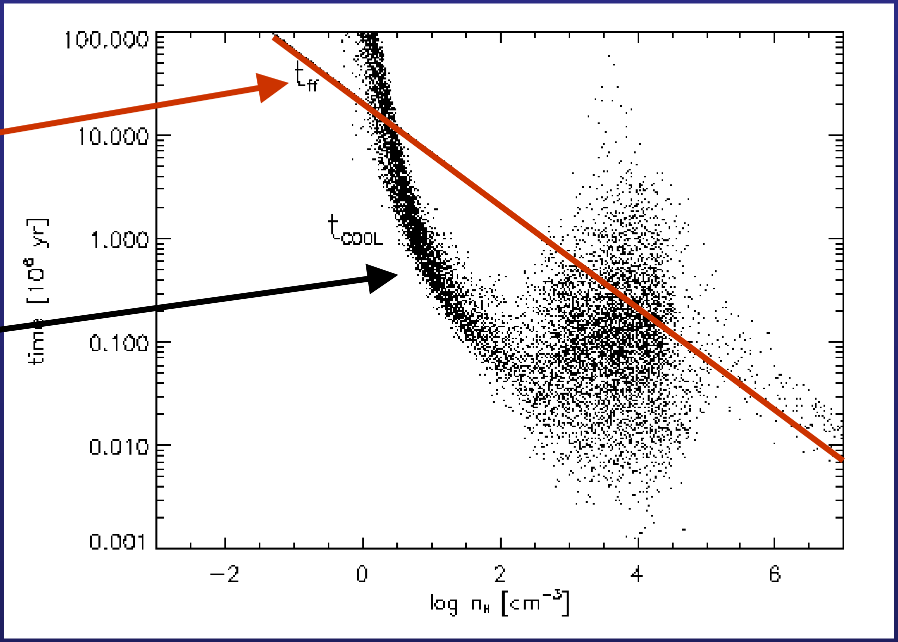
A Tale of Two Timescales

- Consider the cooling and freefall times:

Timescale vs. n

t_{ff}

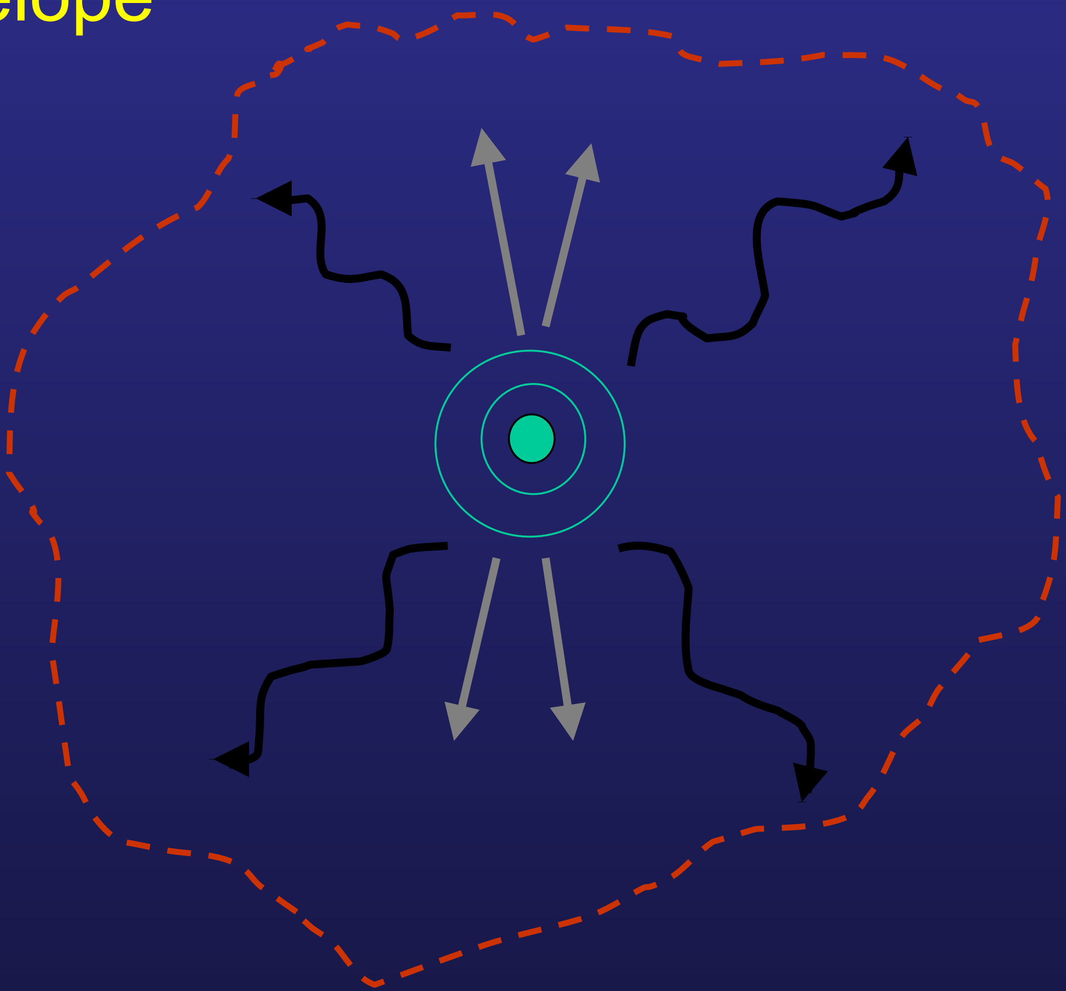
t_{cool}



- Gas particles loiter at: $n \sim 10^3 - 10^4$ cm^{-3}
  - $t_{cool} \sim t_{ff}$
  - Quasi-hydrostatic phase
- Runaway collapse occurs
  - s.t. $t_{cool} \sim t_{ff}$

The Crucial Role of Accretion

• Final mass depends on accretion from dust-free Envelope



Clump:

$M{\sim}M_J$

The Crucial Role of Accretion

- Final mass depends on accretion from dust-free Envelope

- Development of core-envelope structure
  - Omukai & Nishi 1998 , Ripamonti et al. 2002

- $M_{core} \sim 10^{-3}\ M_{o}$ $\longrightarrow$ very similar to Pop. I

- Accretion onto core $\longrightarrow$ very different!

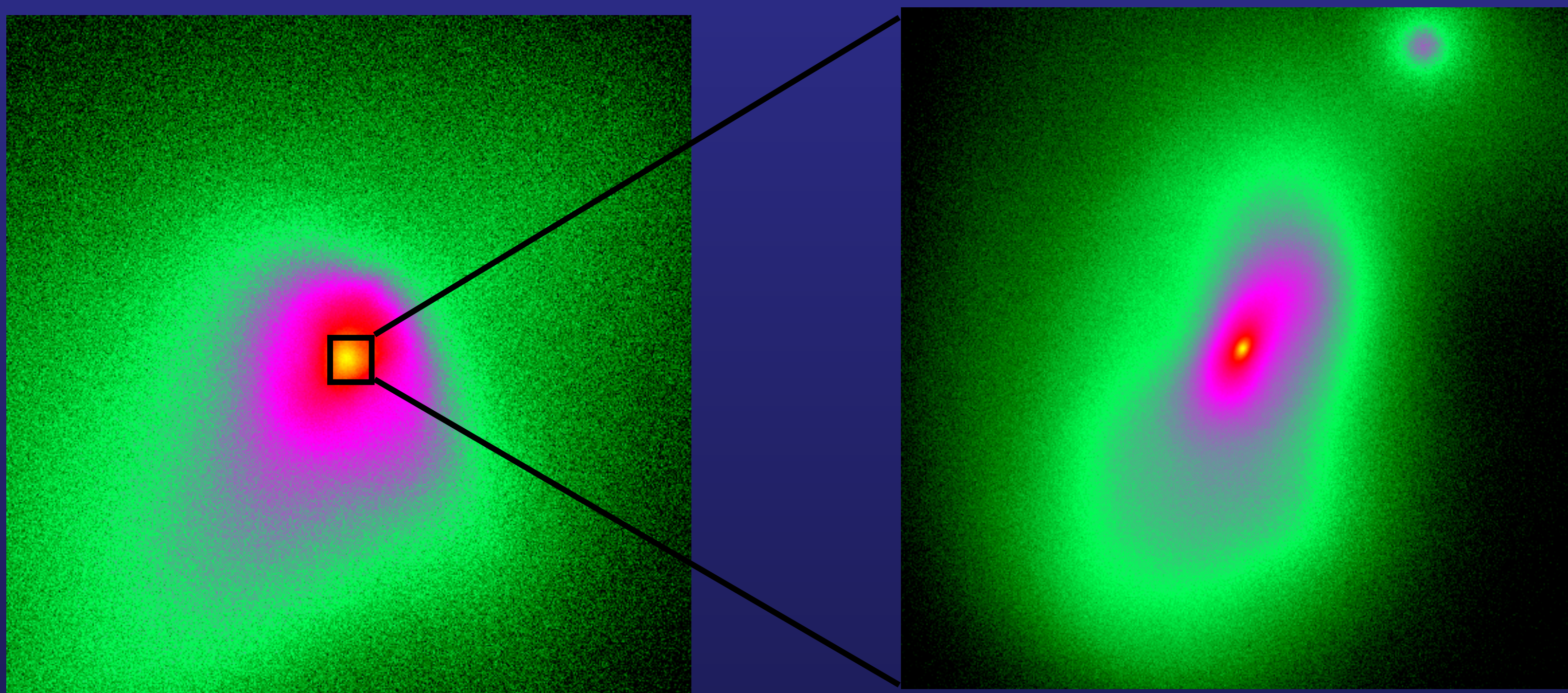
- $dM/dt_{acc} \sim M_J / t_{ff} \sim T^{3/2}$ (Pop I: T ~ 10 K, Pop III: T ~ 300 K)

- Can the accretion be shut off in the absence of dust?

Protostellar Collapse

Bromm & Loeb 2004, New Astronomy, 9, 353

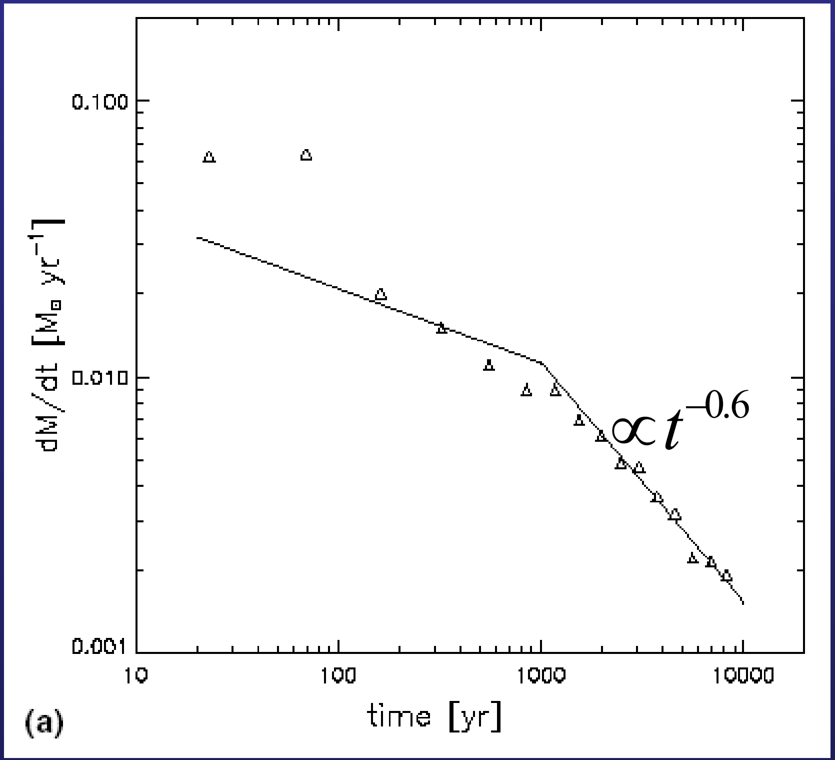
- Simulate further fate of the clump



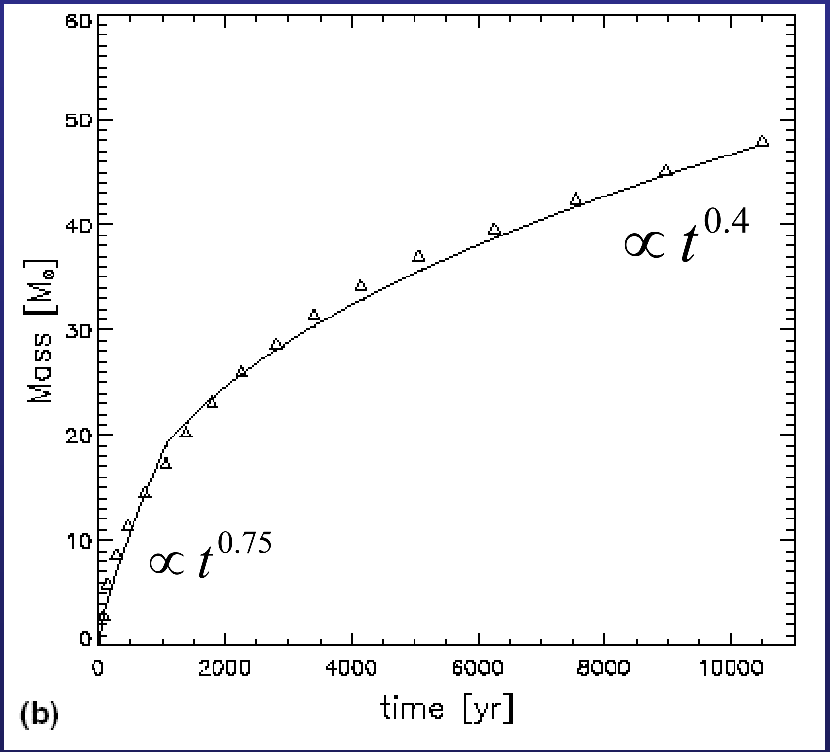
25 pc   0.5 pc

Accretion onto a Primordial Protostar

dM/dt vs. time



M vs. time

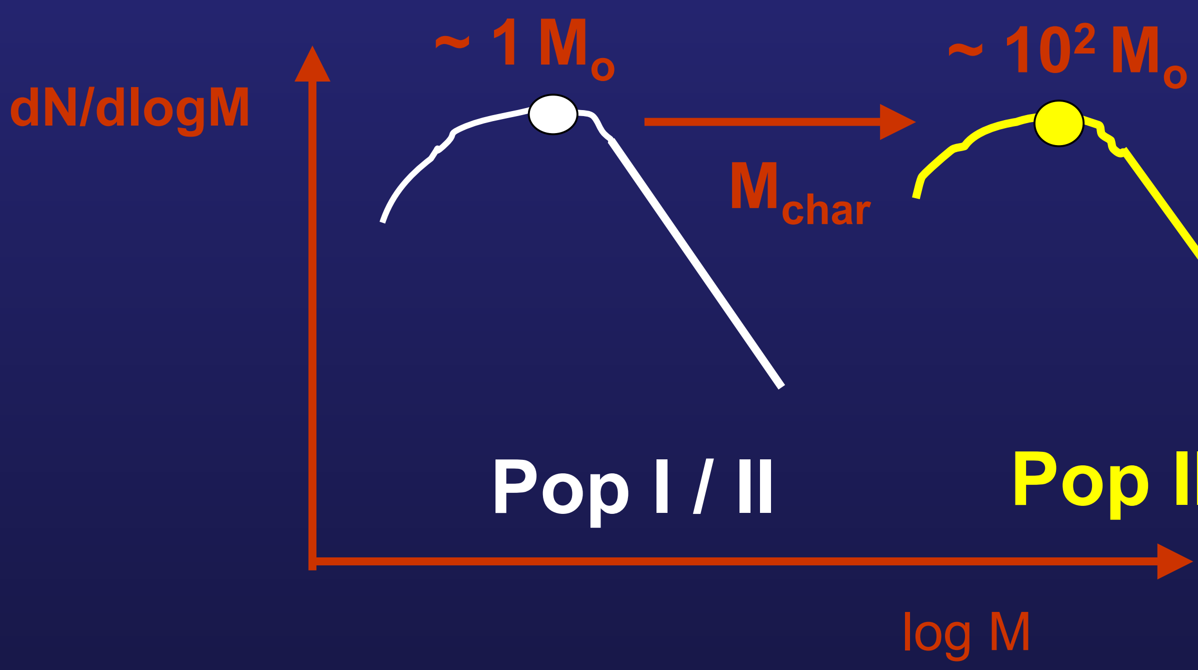


Upper limit: $$M_* \ (t = 3\times10^6\,\mathrm{yr}) \approx 500 M_\odot$$

Population III Star Formation

- Numerical simulations
  - Bromm, Coppi, & Larson (1999, 2002)
  - Abel, Bryan, & Norman (2000, 2002)
  - Nakamura & Umemura (2001)

- Main Result: → **Top-heavy IMF**



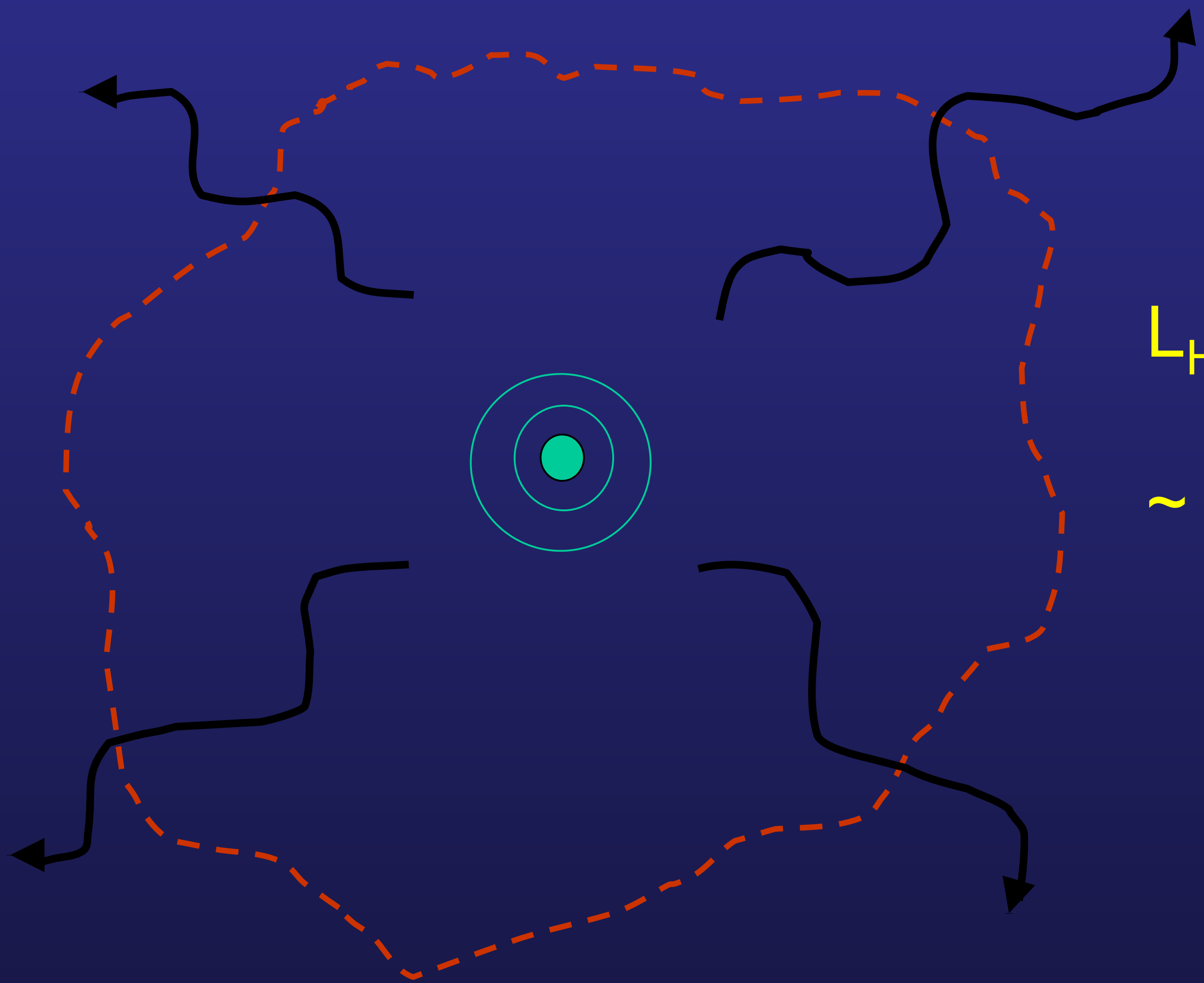
Probing the First Stars with SAFIR:

- Launch in ~2020
- Exquisite sensitivity from mid-IR to mm
- 10 – 20m aperture

→ Can probe H_2 emission from high z

H2 emission during Pop III Formation

- Peak luminosity during accretion phase



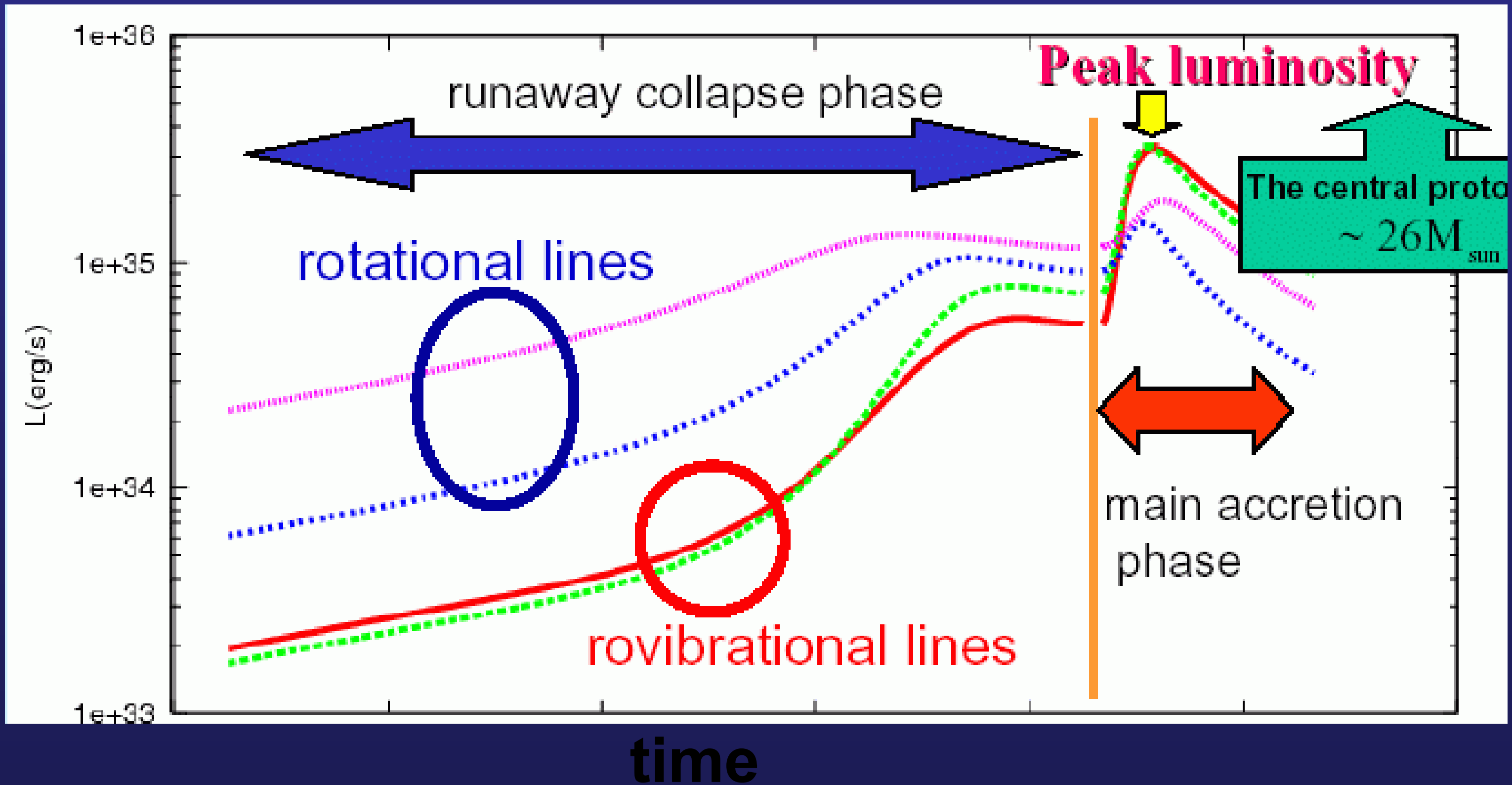
$L_{H2} < L_{acc}$

$\sim 10^{35}$ ergs s^{-1}

H2 emission from First Stars

(Mizusawa, Nishi, & Omukai 2004, PASJ in press)

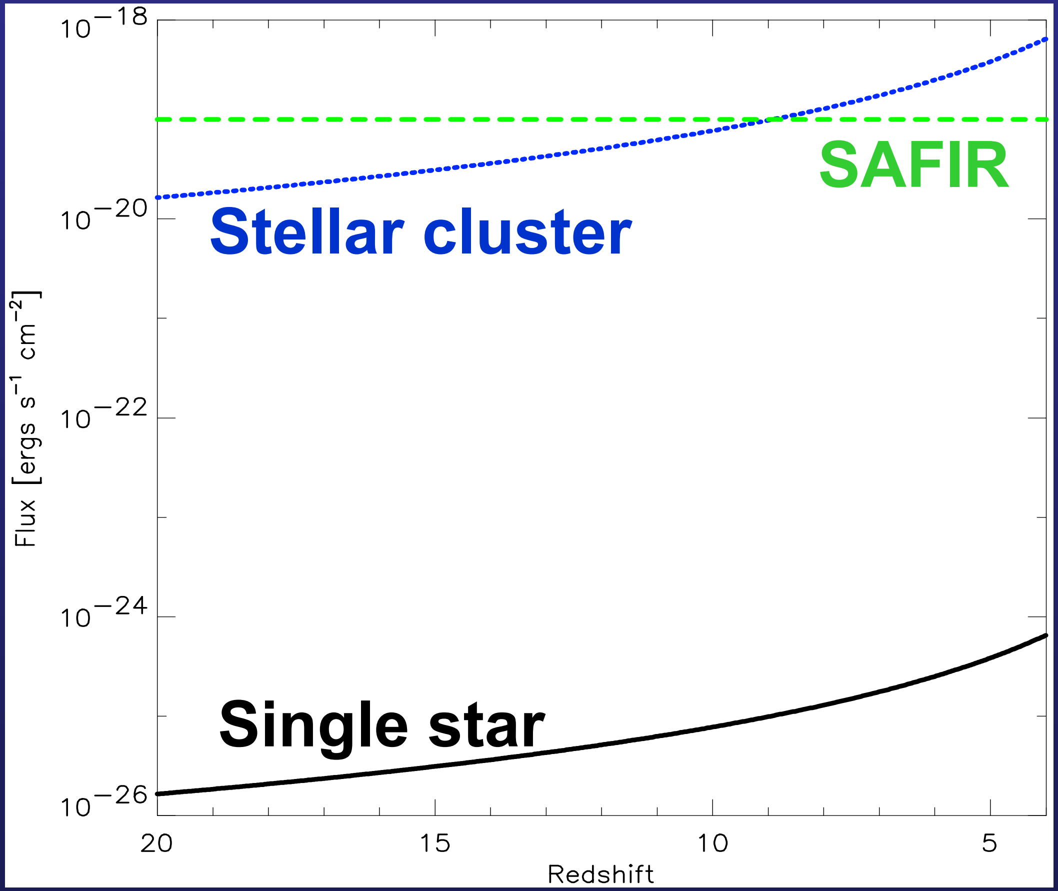
H2 line luminosity vs. time



- initial collapse: pure rotation (~10mu) → FIR
- accretion phase: rovibrational (~3mu) → 50mu

Probing the Birth of Pop III stars

Predicted H2 line flux vs. redshift



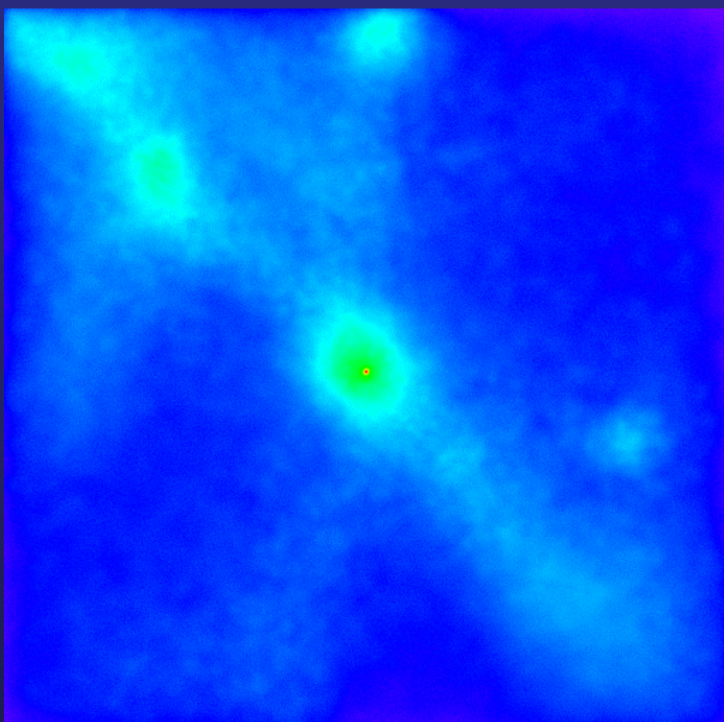
Need > 10^6 stars

→ Can a massive Pop III cluster form?

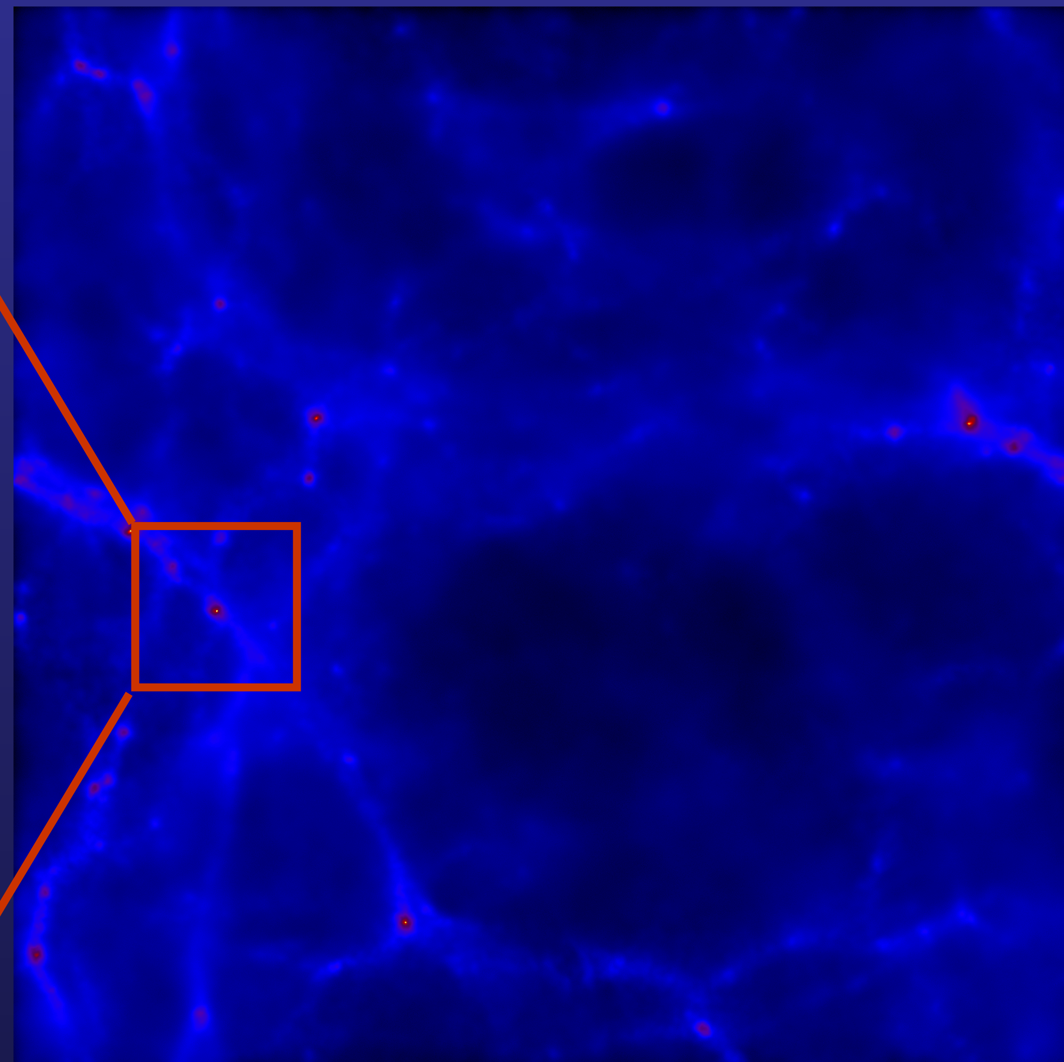
The First Supernova Explosions

(Bromm, Yoshida & Hernquist 2003, ApJ, 596, L135)

$M \sim 10^6 M_o$

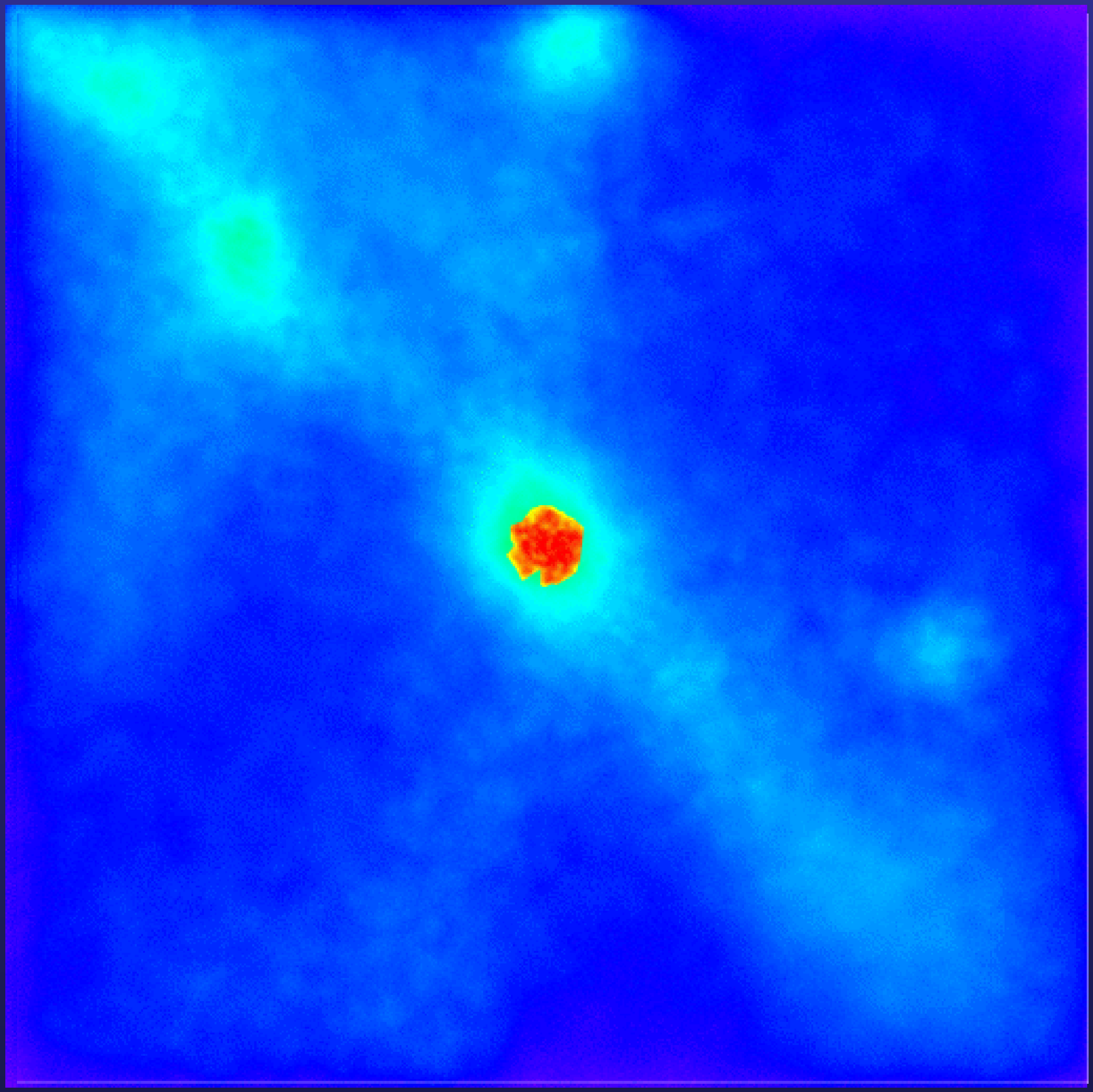


1 kpc



~ 7 kpc

HII Regions around the First Stars

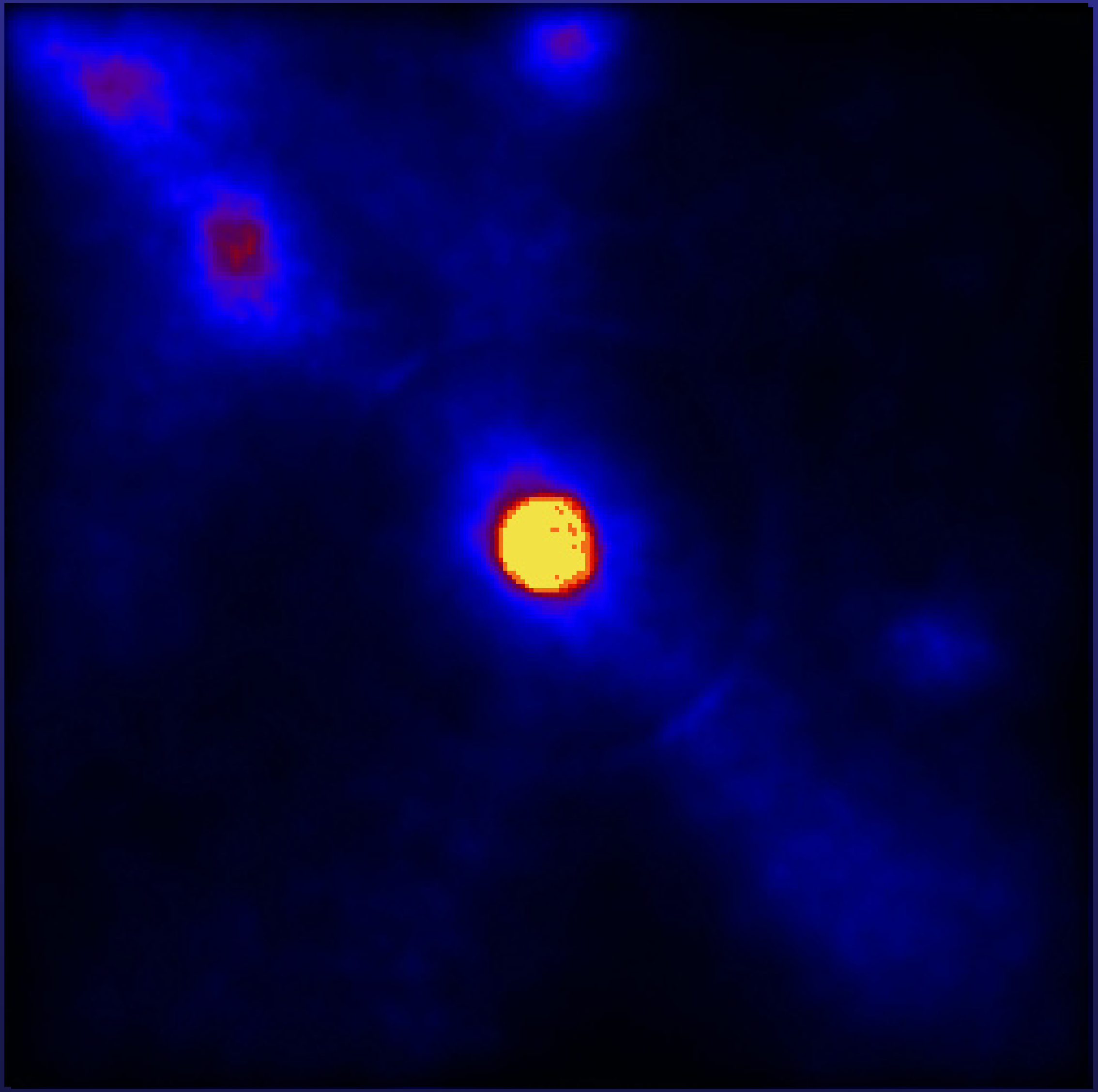


1 kpc

The First Supernova-Explosion

Gas density

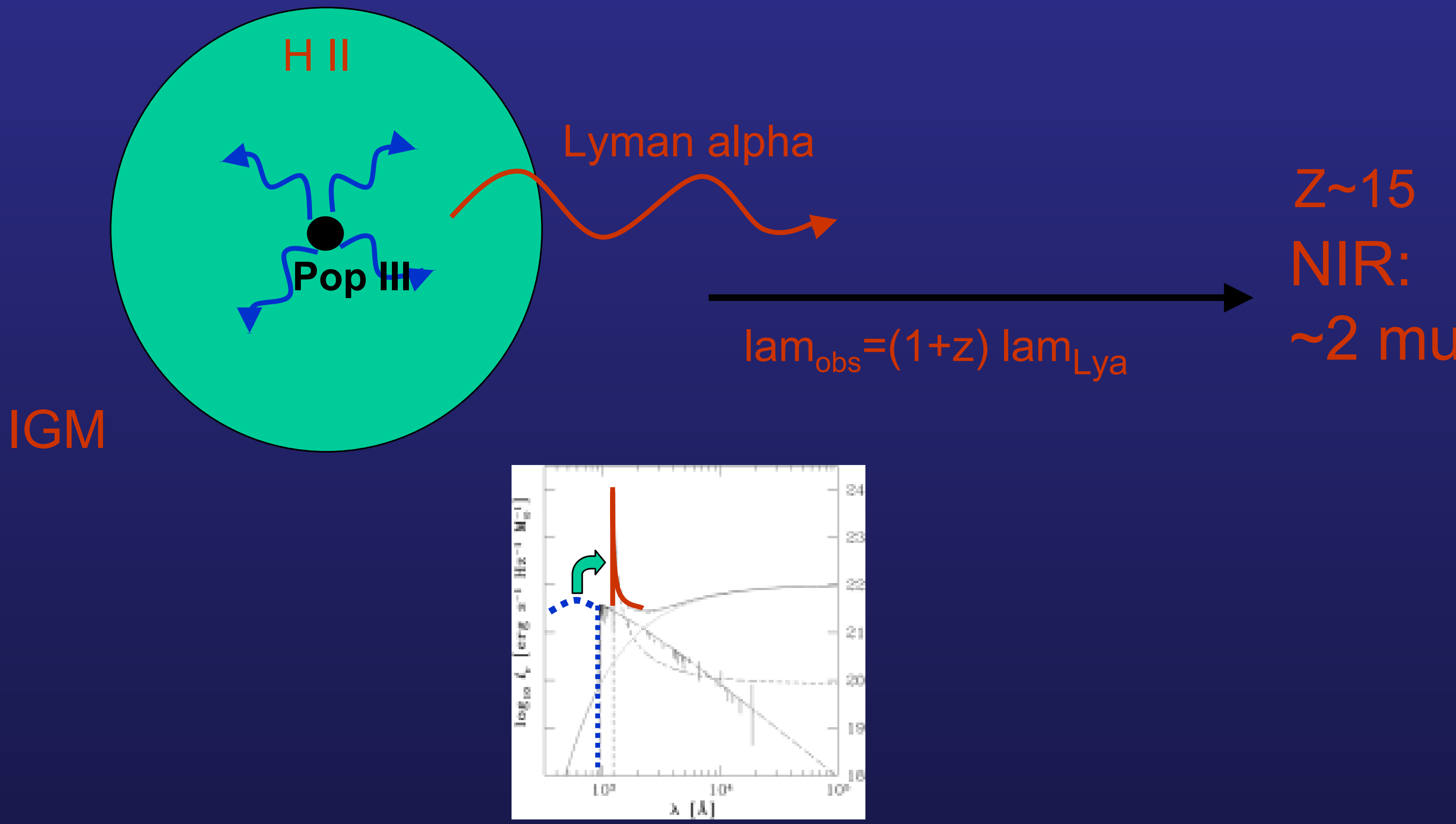
~ 1 kpc



- $E_{SN} \sim 10^{53}$ ergs
- Complete Disruption (PISN)

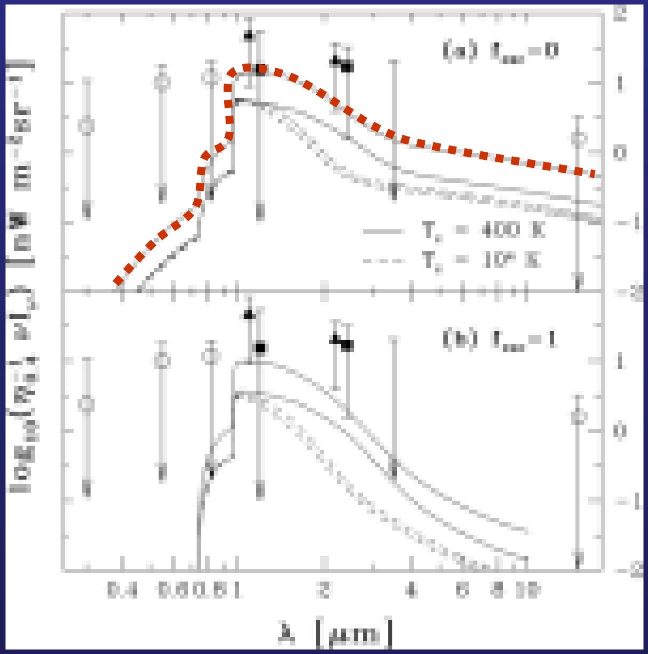
First Stars and Cosmic Near-IR Background

(Santos, Bromm, & Kamionkowski 2002, MNRAS, 336, 1082)



First Stars and Cosmic Near-IR Background

Flux vs. wavelength



- Essential features:
  - Broad: optical → mid-IR
  - Most stellar photons
    → reprocessed → NIR
- NIR/mid-IR background
  → probe of first stars:

  - escape fraction
  - end of Pop III SF epoch (z > 7)

Summary

- Primordial gas typically attains:
  - **$T \sim 200 - 300$ K**
  - **$n \sim 10^3 - 10^4$ cm^{-3}**
- Corresponding Jeans mass: **$M_J \sim$ few x 10^2 M_o**

- Pop III SF might have favored *very massive stars*

- Detecting H2 emission from formation process challenging

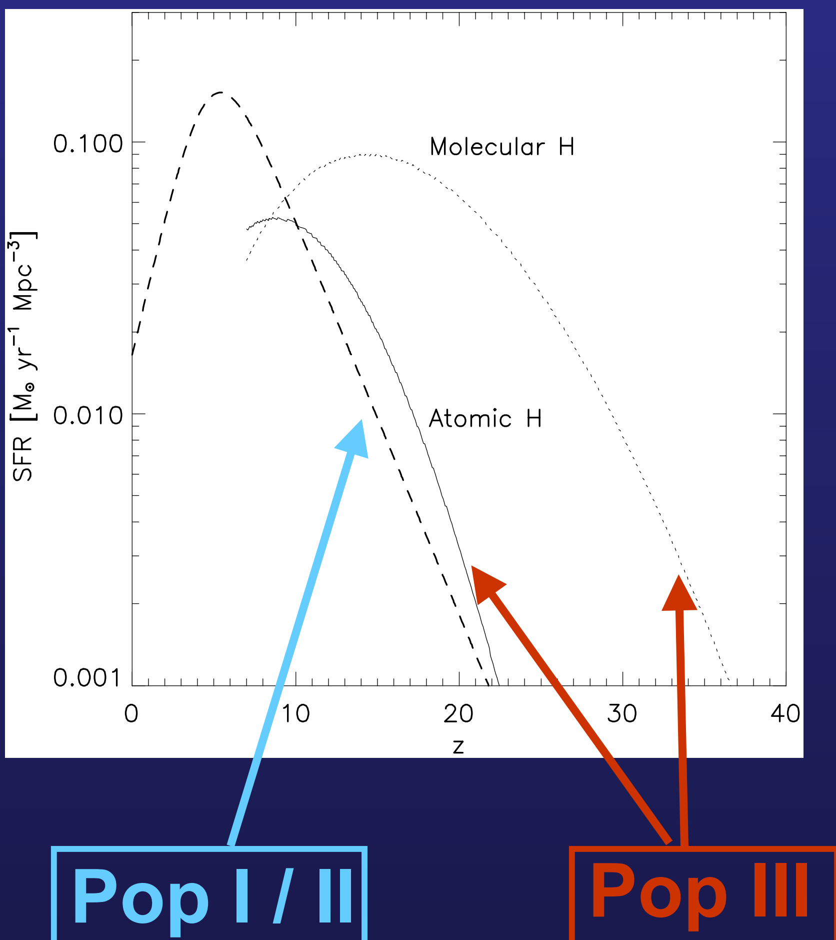
- PISNe completely disrupt mini-halos and enriches surroundings

- Cosmic infrared background sensitive probe of first stars

Cosmic Star Formation History

(Mackey, Bromm & Hernquist 2003, ApJ, 586, 1)

Comoving SFR vs. redshift



(Springel & Hernquist 2003)

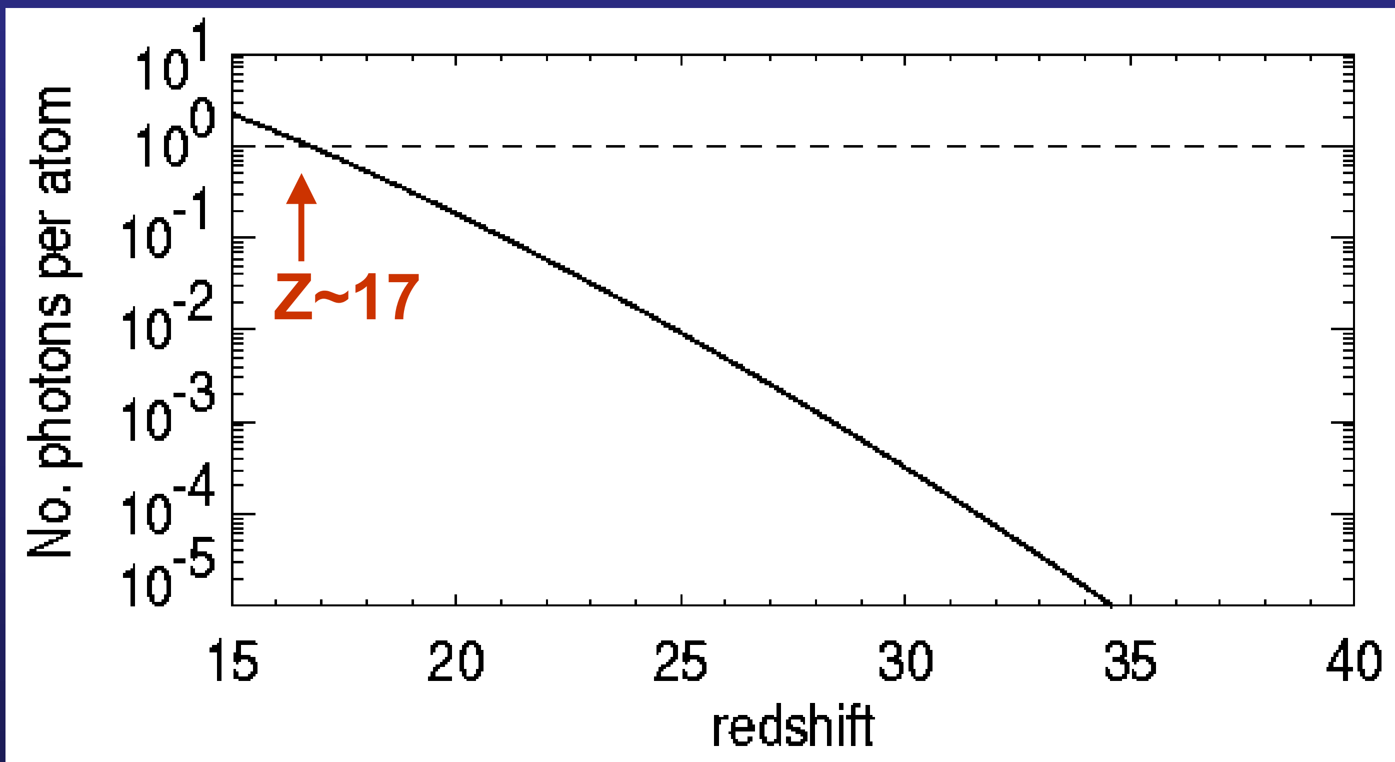
- 2 modes of SF:
  - Pop III → VMS
  - Pop I / II → normal stars

- Pop III SF possible in halos with:
  - $T_{vir} < 10^4$ K → molecular cooling
  - $T_{vir} > 10^4$ K → atomic H cooling

Early Reionization of the Universe

(Yoshida, Bromm & Hernquist 2004)

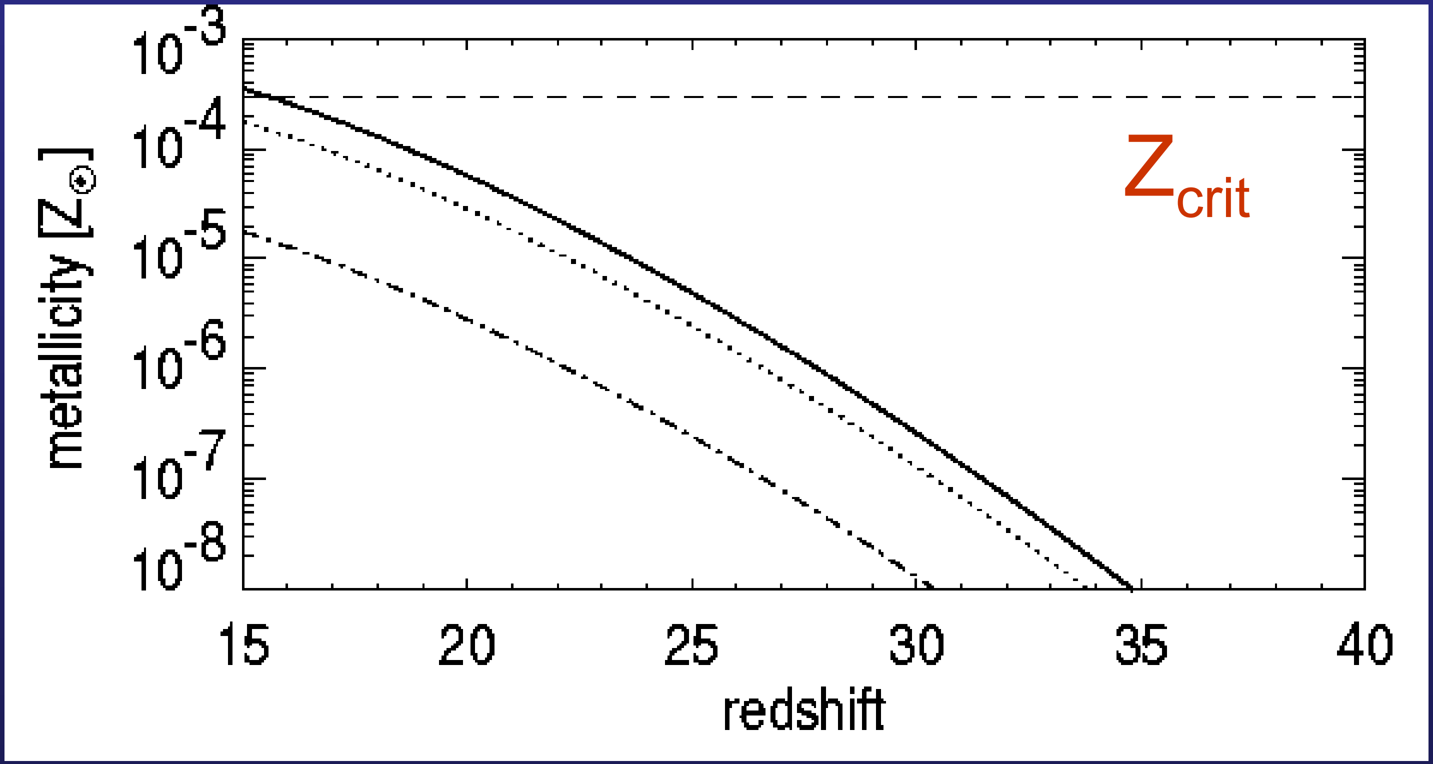
Photons per H atom vs. redshift



The Pop III ⟶ Pop II Transition

(Yoshida, Bromm & Hernquist 2004)

IGM Metallicity vs. redshift



$z_{tran} \sim 15$

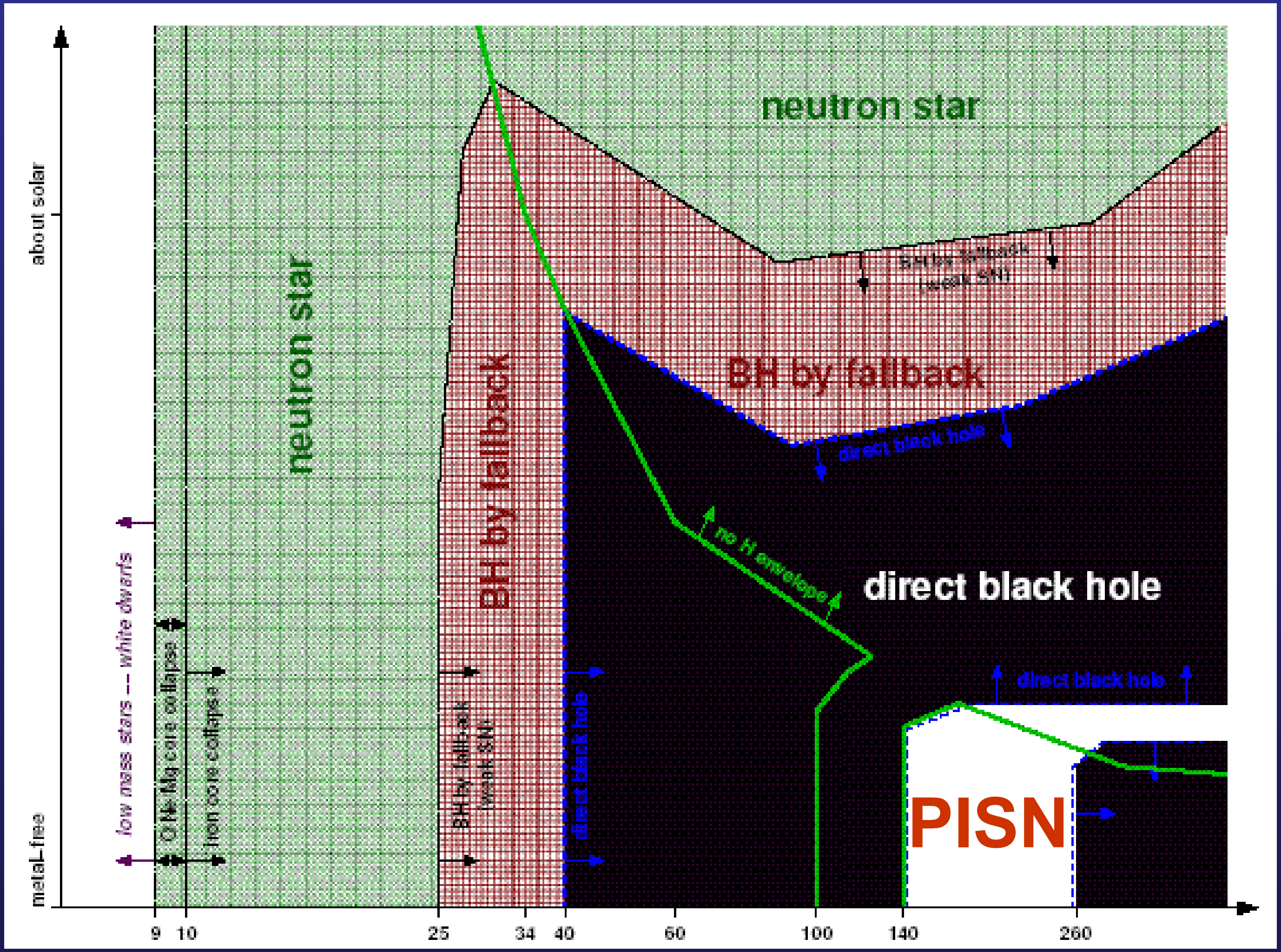
The Death of the First Stars:

(Heger et al. 2002)

Pop I

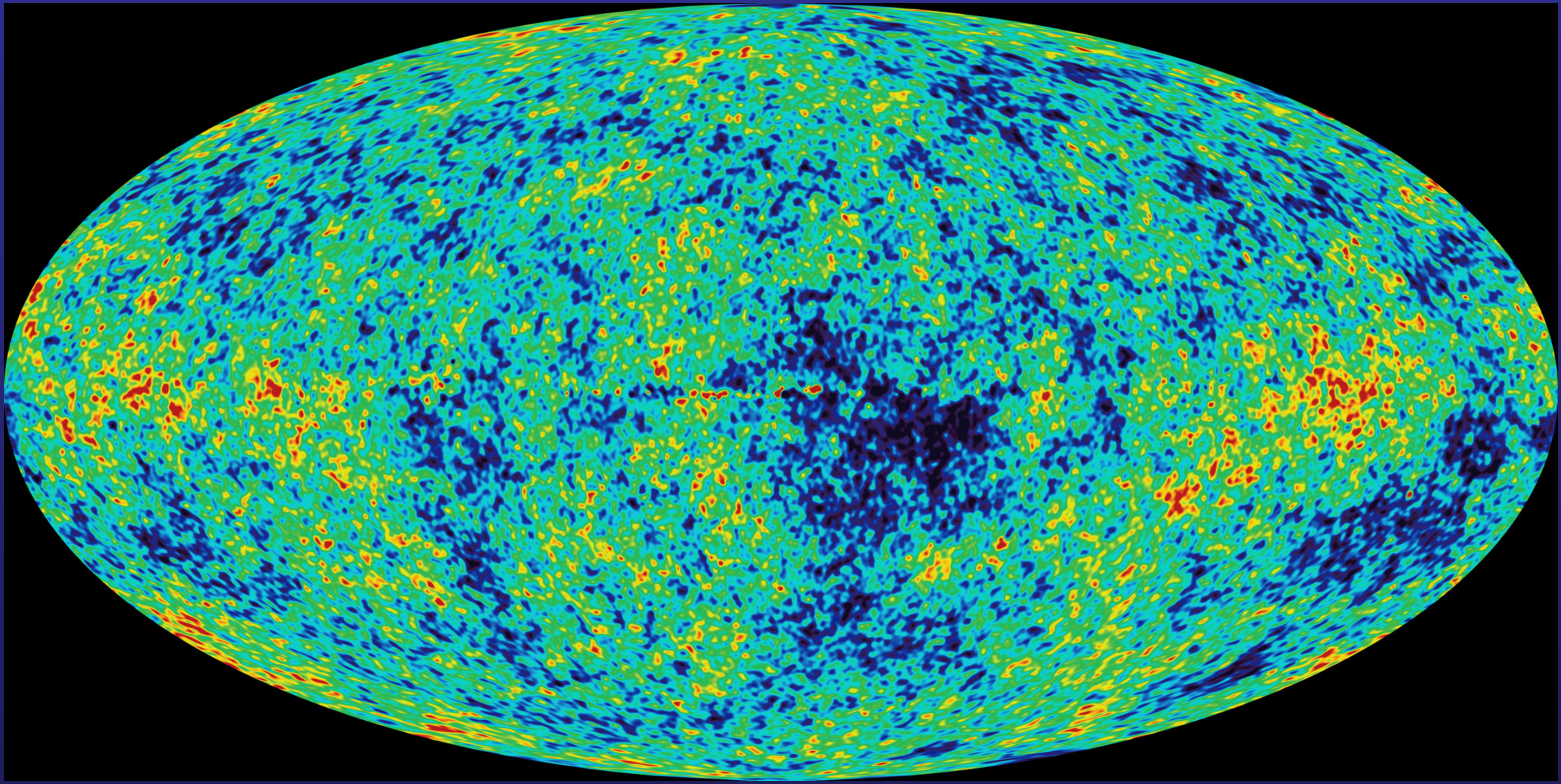
Z

Pop III



Initial Stellar Mass

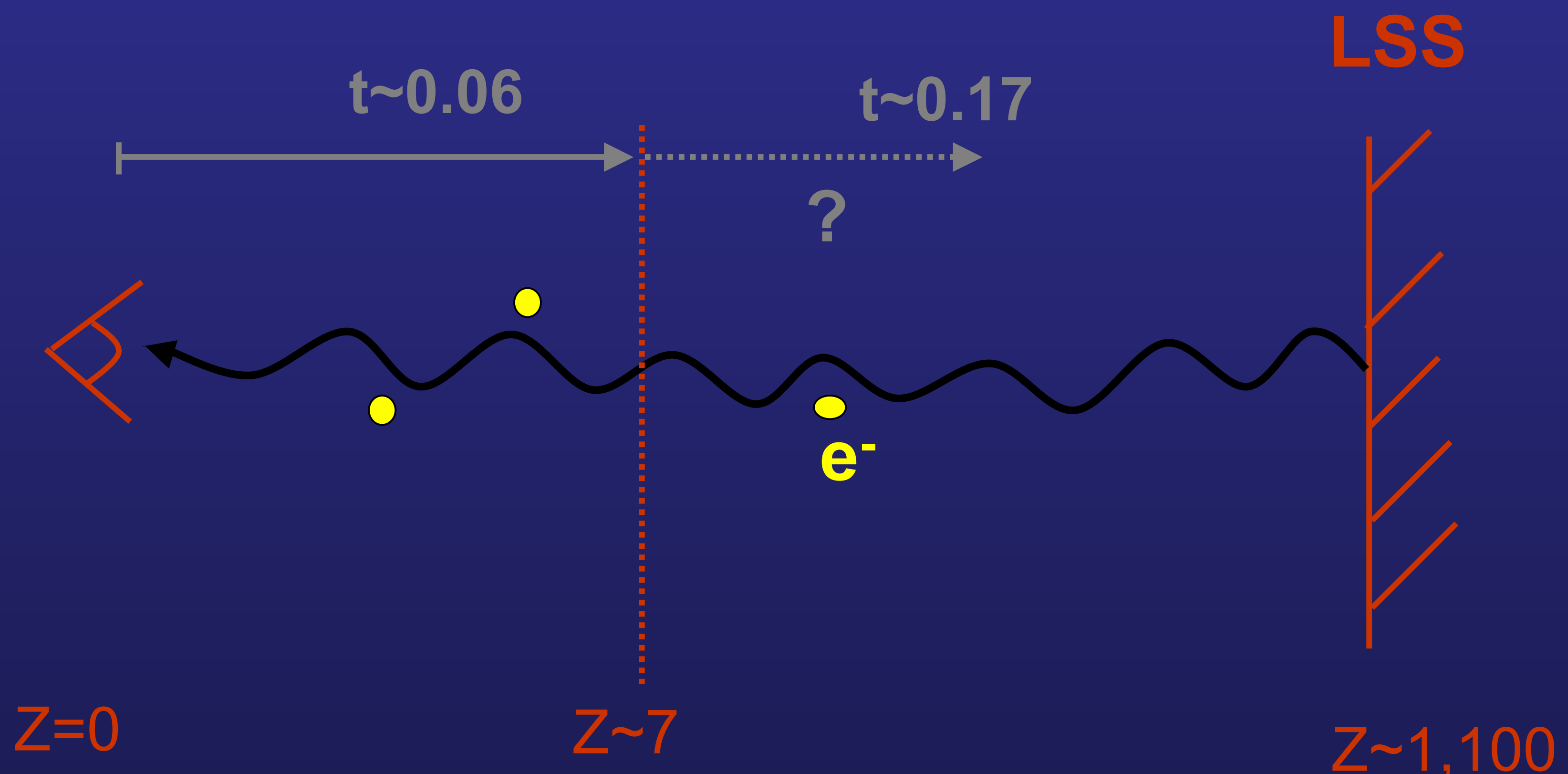
Wilkinson Microwave Anisotropy Probe:



Polarization ⟶ optical depth to Thomson scattering:

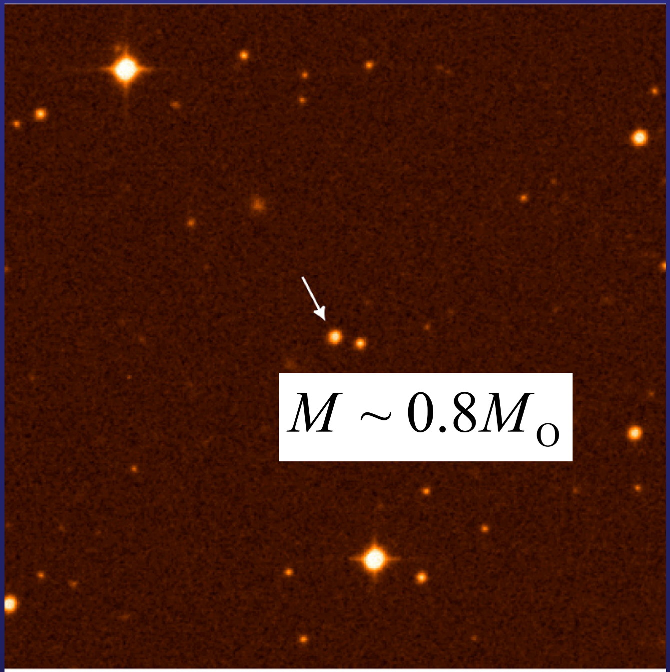
$(\tau = 0.17 \pm 0.04)$ ⟶ **Signature of the First Stars**

CMB photon-scattering from free electrons



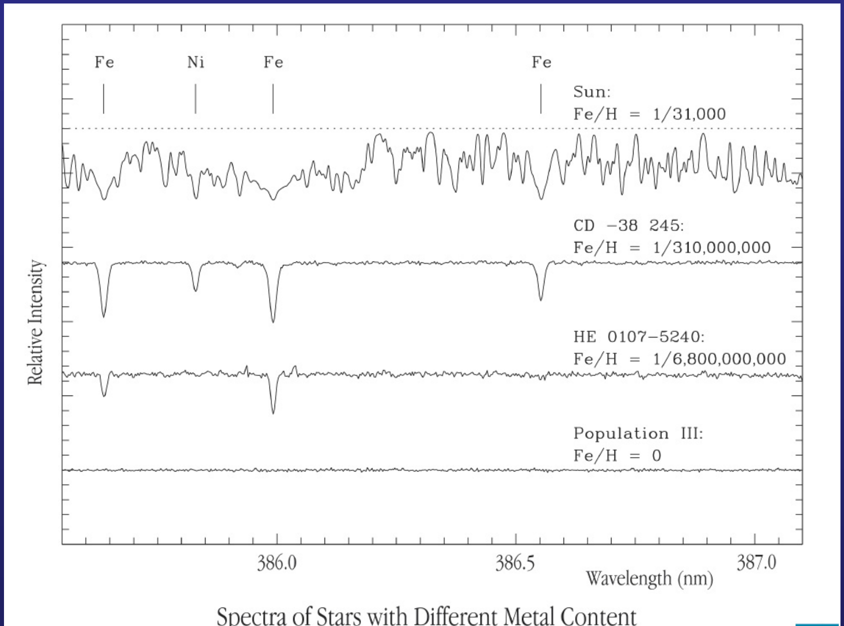
Relic from the Dawn of Time:

- **HE0107-5240**: [Fe/H] = - 5.3 (Christlieb et al. 2002)



The Very Metal-Deficient Star HE 0107-5240

ESO PR Photo 25a/02 (30 October 2002) ©European Southern Observatory



Spectra of Stars with Different Metal Content

ESO PR Photo 25b/02 (30 October 2002) ©European Southern Observatory

- How could such a low-mass star have formed ?

Forming the First Low-mass Stars:
(Bromm & Loeb 2003, Nature 425, 812)

- Abundance pattern:
  - HE0107-5240
  - very Fe-poor
  - very C/O-rich

- Pop III ⟶ Pop II:
  - driven by: CII, OI (fine-structure transitions)

- Minimum abundances:
  - [C/H] ~ -3.5
  - [O/H] ~ -3.1
  - Identify truly 2nd gen. stars!